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THE MOTION OF GASES IN THE SUN'S ATMOSPHERE

PART II. ON THE WESTWARD TILT OF PROMINENCES

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ABSTRACT. From measurements of 1346 absorption markings the authors find that prominences are rarely perpendicular to the sun's surface. The majority of prominences have a tilt towards the west of the vertical, although there are cases of eastward tilt and no tilt. The average tilt found, by proper weighting, from all the measurements is 8°W. An explanation of the origin of the tilt has been offered; and on the basis of this explanation it has been suggested that most stable prominences probably originate in the deep interior of the sun.

In recent years the geometrical aspect of the appearance of solar prominences during their passage across the disc has received a considerable measure of attention from T. Royds and his collaborators at Kodaikanal and from L. d'Azambuja and his co-workers at Meudon, and several useful observational facts have emerged from their investigations. One interesting conclusion brought out by these researches is that there is a marked dissymmetry in the behaviour of prominences projected on the sun's disc in regard to the two halves of the disc separated by the central meridian. From a statistical study of the measures of areas of the absorption markings (or filaments, as they are sometimes called) photographed in H_α light and lying parallel to the meridians at different heliographic latitudes M. Salaruddin[1] found that the areas at eastern longitudes were less than those at the corresponding western longitudes. At the same time he appears to have noted that the areas of absorption markings attained their minimum values at the central meridian. There is, however, an inherent contradiction between these two conclusions which becomes rather evident when one considers his interpretation of the first conclusion concerning the dissymmetry between the eastern and western areas. Salaruddin attempts to explain this dissymmetry by the tentative suggestion that it may be due to most of the filaments measured to the west being growing ones. This interpretation is obviously unconvincing in view of the artificiality of the supposition upon which it is based. There is no objection against assuming that some prominences may be continuously growing and others continuously decaying during their passage from the east limb to the west limb, so that in the average of a large number of cases the eastern and western areas at corresponding longitudes would be equalised and the minimum of area would necessarily occur at the central meridian. But there appears to be no admissible reason for supposing that prominences prefer to grow or decay only when they happen to be on the one side of the central meridian or the other ; in fact such a supposition would be contrary to the law of chance. From these considerations it seems clear that if there is a true inequality between the eastern and the western areas of filaments, then the minimum of area should occur at some longitude different from the central meridian. Indeed it is difficult to accept with equal confidence both the conclusions of Salaruddin referred to above. We have, however, verified by a personal discussion with him that his second conclusion is not intended to be regarded as the result of exact measurements; for the main purpose of his paper he did not require to determine the exact longitude at which the area of an absorption marking became minimum.

If one makes a careful determination of the longitude at which the area of a dark marking becomes minimum, one definitely finds that this longitude, in the vast majority of cases, does not coincide with the central meridian: Mme. M. d'Azambuja-Roumens[2] has found this in her measurement of 171 selected markings and we have arrived at the same conclusion after examining upwards of 1300 filaments which have been studied for the purposes of the present investigation. From the above-mentioned work Roumens concludes that the majority of absorption markings present their minimum area at some longitude to the east of the central meridian and derives a weighted average value of 10°E for this longitude. This result is obviously of the same nature as the dissymmetry referred to above which manifests itself in the increase of the western areas over the eastern areas at corresponding longitudes. In fact Roumens has offered for both these observations a very plausible explanation based on the hypothesis that prominences have a systematic westward tilt or inclination to the vertical at the points where they stand on the sun's surface, so that the average value of 10° found for the eastern longitude at which dark markings present their minimum area or breadth signifies that the average tilt of prominences is 10° towards the west.* It is to be noted, however, that this hypothesis involves a departure from the commonly accepted picture of a prominence. Usually a prominence is regarded as a thin flame (its height and breadth being considerably greater than its depth) resembling a fish-tail in shape and standing with its plane normal to the sun's surface. Since the assumption of the westward tilt is a notable departure from the accepted view about prominences one would naturally like to be certain that such a departure is really necessary and inevitable.

* As will be evident from the next two paragraphs this conclusion is to be regarded as provisional for the time being, for it depends upon whether the markings measured by Roumens were parallel to the meridians or inclined to them.

In a recent paper M. Waldmeier [3] has contended that it is quite unnecessary to make the assumption that prominences are systematically inclined towards the west of the vertical and that it is perfectly possible to account for the above-mentioned observation of Roumens from considerations of simple spherical trigonometry. Waldmeier's argument is briefly as follows : A prominence is a thin flame standing with its plane normal to the surface of the sun, *i.e.*, it has no tilt to the vertical. At the equator the corresponding filament makes an angle of 90° with the parallels of latitude, but at higher latitudes this angle progressively decreases towards the pole as is well known from observation. Let ϕ be the heliographic latitude at which the filament occurs, θ its inclination to the parallels of latitude and d the longitude (counted from the central meridian) at which the filament appears at its narrowest. Then from Fig. 1 it is easily seen that d is that longi-

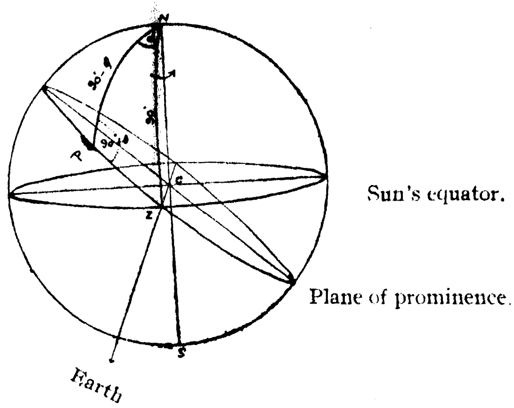


FIGURE 1

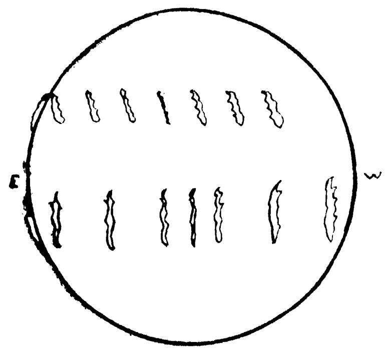
tude at which the length of the filament, prolonged if necessary, would pass through the centre of the disc and in this position the following relation must hold among the quantities d, ϕ and θ :

$$\tan d = \sin \phi / \tan \theta.$$

Now Roumens says in her note that she has used almost entirely filaments of the equatorial belt so that the average latitude of the filaments examined by her may be taken to be about 20°. Then, using the average value of θ obtained from observational data for latitude 20°, one obtains from the above furmula $d = 13°$, which is in excellent agreement with the average value (*viz.*, 10°) of the west tilt derived by Roumens. So far as the geometrical considerations are concerned there can be no doubt that Waldmeier is correct, but the present writers could not feel sure that he is right in assuming that the filaments measured by Roumens really had the average inclination to the parallels of latitude appropriate to latitude 20°, for in her short note in the *Comptes Rendus* sufficient details are not given.

Our doubt was further accentuated by the fact observed by Salaruddin that the western areas of filaments were larger than the eastern areas, although the filaments studied by him were parallel to the meridians. This dissymmetry can, by no means, be explained by Waldmeier's formula. The problem, therefore, appeared to us to be well worth re-examining.

Although generally filaments at the equator are parallel to the meridians and at higher latitudes the inclination of filaments to the meridians increases with the latitude, it is a fact of common observation that quite a number of filaments at latitudes higher than the equator do have little or no inclination to the meridians. Accordingly there appear to be two ways of determining the average tilt of prominences, if such tilt really exists. One way is to select for measurement only filaments parallel to the meridians and determine the longitudes at which they appear at their narrowest ; in this case naturally Waldmeier's geometrical considerations are automatically eliminated, but this method has the disadvantage that one has rather a small number of filaments to work with. The alternative way is to select filaments, which are definitely not parallel to the meridians ; by this method of selection one can obtain a very large number of filaments for measurement, so that one can expect to arrive at a much more reliable average value of the tilt if it exists. It must be noted, however, that in this second method one has to make proper allowances for the effect to be expected from the geometrical considerations set forth by Waldmeier. This will be clear from Fig. 2 in which we have illus-



Successive aspects of prominences
when they traverse the disc

FIGURE 2

trated the variations in the appearance of two types of filaments during their passage from the east limb to the west. The upper half of the diagram shows the successive aspects of a filament inclined to the meridians as it traverses the disc ; and the lower half represents the sequence of aspects of a filament parallel to the meridians. It is assumed that the prominences corresponding to the filaments represented in the diagram have no tilt to the vertical. It is clear that the filament parallel to the meridians attains its minimum breadth at the central meridian, while the filament inclined to the meridians appears narrowest at an eastern longitude where its length points towards the centre of the disc. If, however, the filaments have a tilt towards the west, then the meridional filament should appear narrowest when it is at some eastern longitude instead of the central meridian ; while the inclined filament should be narrowest at some longitude further east of the position shown in Fig. 2. In the case of the meridional filament obviously the tilt is numerically equal to the longitude at which it appears narrowest ; but for the inclined filament the tilt is numerically equal to the difference between the longitude at which it is actually found to be narrowest and the longitude d calculated from the formula $\tan d = \sin \phi / \tan \theta$ by using the appropriate values of ϕ and θ obtained by actual measurement of the filament concerned.

In the present work filaments appreciably inclined to the meridians have been exclusively used. For the purpose of selecting suitable filaments we examined the daily disc spectroheliograms in H_α light and sun charts for about 10 years out of the records of the Kodaikanal Observatory and selected 1346 filaments. Only stable markings were selected for measurement so as to eliminate the uncertainties due to the variation of areas on account of dissipation of parts of markings. The selection was made from a preliminary examination of the bromide prints of photographs. The positives on paper were preferred to the original negatives primarily for the reason that the greatest depth of an absorption marking is better seen as a dark ridge on a positive than as a white marking on a negative; the line of greatest absorption is very helpful in finding the least area or breadth. But there was also the idea of avoiding the risk of damage involved in handling a large number of negatives on glass which form the permanent records of the observatory. After the preliminary examination, the variation of areas of markings, from the east limb to the west limb or until their disappearance, was carefully followed. A little consideration shows that the breadth of a filament must be least when the line of sight lies in the plane of the prominence, which is responsible for the formation of the filament ; and in this position the dark ridge of great absorption lies symmetrically to the wings. This criterion was found to be a dependable guide in finding the longitude at which a filament appeared narrowest. No great difficulty was experienced in choosing the photograph on which a particular marking appeared to have its least breadth. Photographs were thus chosen and then checked with reference to the sketches of markings on the sun charts which are prepared as a routine at this observatory. If the position of a marking showing the minimum breadth appeared on a photograph, then the longitude was measured accurately by means of a glass reseau which had latitudes and longitudes marked on a scale appropriate to the photograph. But photographs are available only at intervals of a day and consequently more often than not it happens that the position of minimum area of a marking occurs at a time which falls within the interval between the times at which photographs are taken on successive days. In such cases the most probable longitudes of markings were estimated by judging whether the minimum areas occurred nearer one day or the other and applying suitable corrections to the longitudes as measured from the photographs. This method of interpolation necessarily introduces a certain amount of uncertainty ; and as the variation due to the sun's rotation is about 13° per day the maximum error involved in any individual estimation may be $\pm 3^\circ$. The measurement of the latitudes of markings could be done with less uncertainty, the procedure followed being in accordance with the usual practice in solar statistics. If a marking was found to lie across a zone of 5° of latitude, the mean of the zone was marked against the marking. If the marking was shorter than a zone, the latitude of the midpoint to the nearest degree was taken as the latitude of the marking. If a marking was long and lay across several zones of latitude, then each portion of the marking lying across a zone was considered to be an individual marking and the mean of the zone noted against each. The inclinations to the parallels of latitude were measured, as is usually done, when the markings were at the central meridian or near it, so that the vitiating influence of the curvature of the sun's surface was eliminated. The values of the inclination, thus obtained, were noted against the markings to the nearest 5°. As it was found difficult to measure the inclinations of markings above latitude 45°, most of the markings chosen were below that latitude.

The observations were arranged in groups according to ranges of latitude and inclinations. The means (λ_m) of individual observations in each group were worked out and are given together with the number of observations in every group in Table I. The calculated values of d according to Waldmeier's formula for different values of ϕ and θ are given in Table II. In Table III are given the residual values $(\lambda_m - d)$ which are the tilts of the markings. Of the 1346 markings measured for this work, 64 indicated no tilt, 237 indicated eastward tilt and 1045 indicated westward tilt ; that is, 78% of the filaments examined showed the existence of a westward tilt. The residual values in Table III vary from group to group both in sign and magnitude. In order to get an idea of the average tilt a general weighted mean of all the group values was worked out by giving appropriate weights according to the number of observations in every group. The weighted mean value thus obtained is $+8^\circ{\cdot}2$ with a probable error of $\pm 0^\circ{\cdot}96$. From the foregoing results it is evident that the majority of prominences do not stand perpendicularly to the sun's surface; they have a predominantly westward tilt, the average value of which is 8°W.

By the time all the computational work in connection with the present paper was completed Waldmeier[4] published a short note in which he admits that Mme. d'Azambuja-Roumens's conclusion regarding the existence of a westward tilt is correct in view of certain facts which she has communicated to him in private correspondence and also in view of what she has said in a second, somewhat more detailed, paper[5] which was not known to him when he criticised her conclusion. This second paper of Mme. d'Azambuja-Roumens had

TABLE I

θ / ϕ	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°	80°
	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m	λ_m
	o	o	o	o	o	o	o	o	o	o	o	o	o	o
0°-5°	— (-)	18 (7)	28 (3)	27 (4)	14 (3)	25 (13)	30 (5)	16 (9)	20 (4)	22 (6)	37 (4)	23 (7)	36 (1)	10 (2)
5°-10°	26 (2)	12 (4)	9 (3)	26 (6)	24 (5)	23 (13)	12 (6)	20 (17)	24 (5)	25 (5)	22 (1)	23 (6)	26 (2)	30 (1)
10°-15°	7 (1)	25 (1)	17 (5)	22 (11)	15 (13)	21 (24)	20 (17)	18 (25)	19 (10)	25 (20)	22 (8)	23 (12)	7 (2)	— (-)
15°-20°	7 (3)	16 (6)	23 (6)	20 (10)	27 (17)	22 (26)	20 (23)	22 (38)	20 (15)	27 (24)	27 (6)	26 (12)	28 (5)	23 (4)
20°-25°	13 (2)	37 (5)	27 (10)	20 (16)	17 (14)	28 (31)	24 (34)	24 (44)	22 (26)	28 (41)	34 (14)	31 (12)	30 (3)	34 (3)
25°-30°	— (-)	28 (3)	29 (7)	31 (14)	22 (16)	30 (28)	25 (35)	32 (38)	30 (18)	35 (37)	33 (12)	32 (20)	34 (9)	23 (2)
30°-35°	65 (1)	40 (6)	34 (5)	31 (8)	35 (12)	31 (33)	28 (27)	43 (17)	31 (21)	33 (24)	35 (9)	38 (10)	30 (3)	42 (1)
35°-40°	50 (1)	36 (3)	41 (2)	50 (7)	30 (3)	37 (14)	34 (15)	44 (10)	35 (5)	37 (18)	36 (8)	40 (8)	50 (2)	35 (1)
40°-45°	— (-)	30 (4)	36 (3)	39 (3)	45 (1)	47 (7)	39 (7)	36 (7)	— (-)	41 (12)	37 (3)	39 (5)	— (-)	— (-)
45°-50°	— (-)	60 (1)	— (-)	26 (2)	50 (3)	— (-)	— (-)	52 (4)	25 (1)	53 (5)	37 (2)	40 (1)	— (-)	— (-)
50°-55°	— (-)	— (-)	— (-)	— (-)	— (-)	— (-)	25 (1)	55 (2)	— (-)	70 (1)	— (-)	— (-)	— (-)	— (-)
55°-60°	— (-)	40 (1)	— (-)	— (-)	— (-)	— (-)	35 (1)	— (-)	— (-)	— (-)	— (-)	— (-)	— (-)	— (-)

Figures in brackets represent the number of observations

TABLE II

θ / ϕ	15° d	20° d	25° d	30° d	35° d	40° d	45° d	50° d	55° d	60° d	65° d	70° d	75° d	80° d
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0°- 5°	9	6	5	4	3	3	3	2	2	1	1	1	1	1
5°-10°	26	20	16	13	11	9	7	6	5	4	4	3	2	2
10°-15°	39	31	25	21	17	14	12	10	8	6	5	4	3	2
15°-20°	48	40	33	27	23	20	17	14	12	10	8	6	5	3
20°-25°	55	46	39	34	29	25	21	18	14	12	10	8	6	4
25°-30°	60	52	45	38	34	29	25	21	18	15	12	10	7	5
30°-35°	63	56	49	42	38	33	28	24	21	17	14	11	8	5
35°-40°	66	59	53	46	40	36	31	27	23	19	16	12	9	6
40°-45°	68	62	55	49	44	39	34	30	25	21	17	14	10	7
45°-50°	70	64	58	52	46	41	36	32	27	23	19	16	11	7
50°-55°	—	—	—	—	—	—	39	35	—	25	21	16	—	—
55°-60°	—	67	—	—	—	—	40	—	—	—	—	—	—	—

Table III

θ / Φ	15° λ_m-d	20° λ_m-d	25° λ_m-d	30° λ_m-d	35° λ_m-d	40° λ_m-d	45° λ_m-d	50° λ_m-d	55° λ_m-d	60° λ_m-d	65° λ_m-d	70° λ_m-d	75° λ_m-d	80° λ_m-d
	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0°-5°	—	+12	+23	+23	+11	+22	+27	+14	+18	+21	+36	+22	+35	+9
5°-10°	0	−8	−7	+13	+13	+14	+5	+14	+19	+21	+18	+20	+24	+28
10°-15°	−32	−6	−8	+1	−2	+7	+8	+8	+11	+19	+17	+19	+4	—
15°-20°	−41	−24	−10	−7	+4	+2	+3	+8	+8	+17	+19	+20	+23	+20
20°-25°	−42	−9	−12	−14	−12	+3	+13	+6	+8	+66	+24	+23	+24	+30
25°-30°	—	−24	−16	−7	−12	+1	0	+11	+12	+20	+21	+22	+24	+18
30°-35°	+2	−16	−15	−11	−3	−2	0	+19	+10	+16	+21	+27	+22	+37
35°-40°	−16	−23	−12	+4	−10	+1	+3	+13	+12	+18	+20	+28	+41	+29
40°-45°	—	−32	−19	−10	+1	+8	+5	+6	—	+20	+20	+25	—	—
45°-50°	—	−4	—	−26	+4	—	—	+20	−2	+30	+18	+24	—	—
50°-55°	—	—	—	—	—	—	−14	+20	—	+45	—	—	—	—
55°-60°	—	−27	—	—	—	—	−5	-	—	—	—	—	—	—

also escaped our notice ; but we have now read this paper and have not found in it any clear indication as to whether she has used meridional markings or markings inclined to the meridians in her determination of the west tilt of prominences. The second paper is, as far as we can see, an elaboration of her shorter note in certain respects, but her method of determining the tilt is precisely the same as we have described earlier in the present paper. Consequently, if she has used mainly filaments inclined to the meridians for her work, then her average value of 10°W for the tilt must be substantially in error, for her method does not make allowances for the geometrical effect pointed out by Waldmeier. But since our value of 8° W agrees closely with her determination we are led to the conclusion that she must have used mostly filaments parallel to the meridians, so that the geometrical effect was practically eliminated. The fact that Mme. d'Azambuja-Roumens's value is slightly higher than ours is probably due to her having used some inclined filaments as well without, however, applying necessary corrections for the geometrical effect. Combining Mme. d'Azambuja-Roumens's and our results we may, therefore, conclude that filaments both of the meridional and inclined types show that prominences have a predominantly westward tilt to the vertical.

As the foregoing paragraphs have shown, it is not difficult to establish from observational material the prevalence of a westward tilt in prominences, but it is not so easy to discern with certainty the cause of this phenomenon. One of the explanations so far available of the genesis of the tilt is due to Mme. d'Azambuja-Roumens who discovered it. She bases her tentative explanation on the assumption that the top of a prominence rotates from east to west with a higher angular velocity than the bottom of the prominence. We find, however, very little conclusive evidence in support of this hypothesis. A comparison of all available determinations of the angular velocity of rotation, made from the variation of the positions of sunspots, faculae, filaments, prominences, etc., indicates practically the same velocity of rotation at the heights corresponding to these phenomena ; and even if one claims that there is a tendency for the angular velocity to increase with altitude, there is scarcely any reason for concluding that the rate of increase with altitude is anything but extremely small. This being the case, an average tilt of 8°W would require several days to come into existence through the mechanism envisaged by d'Azambuja-Roumens, and the life of those prominences which show tilts of the order of 30° would have to be much longer than is warranted by observation. It must be mentioned, however, that the determinations of the east-west velocity in the upper parts of prominences made by J. Evershed[6] from the Doppler displacements of the H and K lines have given angular velocities at least 1° per day higher than the angular velocity determined from sunspots. Some other observers also have obtained like results from similar spectroscopic measurements. This may at first sight suggest that the top of a prominence moves much faster than its bottom, and this seems to be the reason for d'Azambuja-Roumens's assumption. But a difference in angular velocity of the order of 1° per day between the top and the base of a prominence would cause a rapid increase in the tilt and therefore a rapid change in the shape of the prominence and the corresponding filament; such rapid changes are, however, not observed in the quiescent prominences and absorption markings which exhibit a remarkable stability of shape. The virtual equality of the angular velocities at the sunspot and prominence levels as derived from the above-mentioned non-spectroscopic determinations and the observed stability of the shape of quiescent prominences and filaments appear to be clear evidence against d'Azambuja-Roumens's hypothesis; there is also no special reason for thinking that the spectroscopic measurements referred to above give the velocity of the bodily movement of the tops of prominences. In fact, the discrepancy between the angular velocity derived from the non-spectroscopic observation of filaments and the angular velocity determined from spectroscopic measurements of prominences may be regarded as an indication that the two methods measure two velocities quite distinct from each other. The non-spectroscopic method gives the apparent bodily movement of spots, filaments, etc., while the spectoscopic method applied to prominences determines the east-west velocity of the constituent atoms resulting from the internal motions of the prominences. The existence of internal motion in prominences is well known and there is little doubt that stable prominences are continually renewed from below. It seems probable that this internal motion is not random and that the atoms describe a cyclic trajectory in a plane more or less inclined to the meridians, so that atoms go up along one arm of the cycle steadily curving westwards until the trajectory becomes horizontal at the top and then descend back to the surface of the sun along the other arm of the cycle. There is good dynamical reason for such cyclic motion which is even necessary for maintaining the shape of stable prominences. On this view the high velocity obtained from spectroscopic mersurements on the upper part of a prominence is the east-west velocity of the radiating atoms in the upper, more or less horizontal, part of their cyclic path, the translatory movement of the prominence being negligible in comparison.

In view of the difficulties pointed out in the above discussion the mechanism suggested by Mme. d'Azambuja-Roumens in order to explain the observed westward tilt of prominences cannot be regarded as satisfactory. The only other explanation of this phenomenon, so far as we are aware, has been given by one of us in a previous paper.[7] In that paper the dynamics of a particle ejected from the interior of the sun, where the angular velocity is much higher than at the surface, has been investigated and it has been shown from the equations of motion that the trajectory of such a particle will be inclined towards the west of the vertical at the point of the sun's surface at which the particle emerges into the coronal atmosphere, provided that the particle was initially projected in a radial direction. It has also been shown that the amount of deflection from the vertical to be expected from theoretical considerations is, on the average, of the same order as the average west tilt derived from observational data by d'Azambuja-Roumens and by us. Without going into further details, which will be found in the afore-mentioned paper, we may, however, mention that this explanation is free from the objections that can be raised against d'Azambuja-Roumens's explanation. The eastward tilt observed in some prominences also follows in a natural way from the equations of motion if the particle starts in a radial direction from some layer of the sun where the angular velocity is the same as the angular velocity observed at the surface; this eastward tilt is, however, very difficult to understand from the mechanism proposed by d'Azambuja-Roumens or from the hypothesis (advocated by some workers) of the existence of permanent east-west currents beyond the chromosphere. The occurrence of no tilt in a few prominences probably indicates that sometimes particles are ejected with an initial bias towards the east or west of the radial direction and this bias is compensated by the deflection to be expected from the equations of motion. But since the majority of prominences have a westward tilt, one may probably conclude, according to the mechanism advocated in the present paper, that stable prominences are generally formed by gases initially ejected in a radial direction from the deep interior of the sun.

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